Capacitance measurements on AC-LGADs (FBK RSD1)

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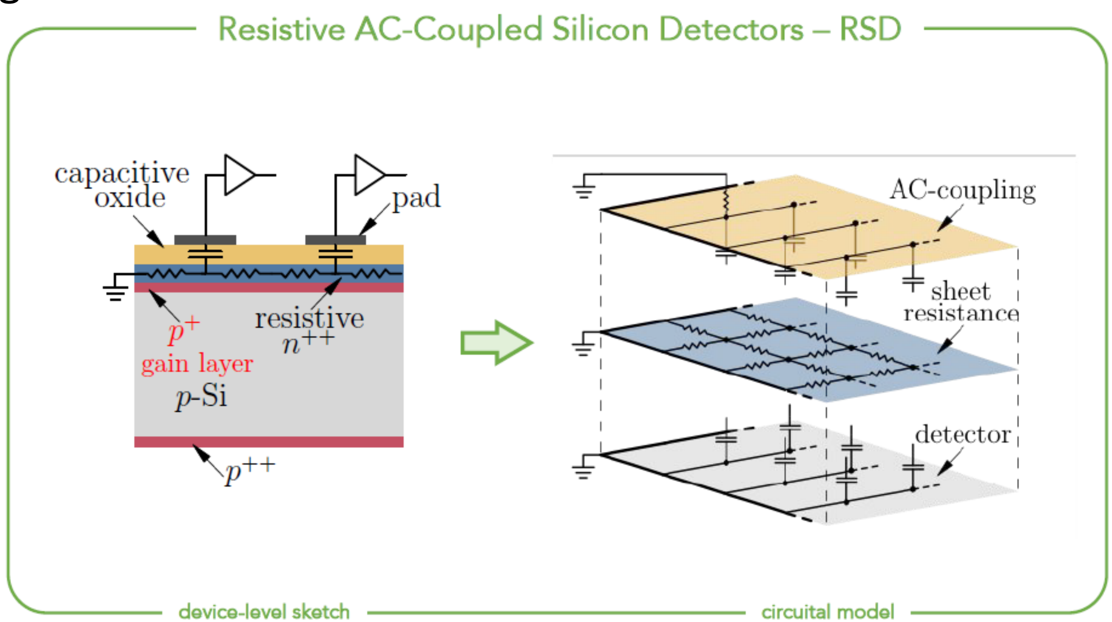
39th RD50 Workshop, 17.-19.11.2021, Valencia&online

Background and motivation

- Low-gain avalanche diodes (LGADs) are studied for ultrafast timing applications and 4D tracking
- In AC-coupled LGADs, also referred to as Resistive Silicon Detectors (RSD), the multiplication layer and n^+ contact are continuous, and only the metal layer is patterned:
  - the signal is read out from metal pads on top of a continuous layer of dielectric
  - the underlying resistive n^+ implant is contacted only by a separate grounding contact



M. Mandurrino, 13th Trento Workshop 2018

Background and motivation

- Low-gain avalanche diodes (LGADs) are studied for ultrafast timing applications
- In AC-coupled LGADs, also referred to as Resistive Silicon Detectors (RSD), the multiplication layer and n^+ contact are continuous, and only the metal layer is patterned:
  - the signal is read out from metal pads on top of a continuous layer of dielectric
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- C-V measurements can be used to probe various capacitances in such sensors:
  - Give an idea of the RC characteristics, interpad and dielectric capacitances etc
  - Also important for the design of readout electronics!

FBK RSD1 production

wafer #	*n* -plus dose	*p* -gain dose	dielectric thickness	*p* -stop dose	substrate	Vbd	Dose [a.u.]
3	A	0.92	L	B	Epi	460	0.05
4	A	0.94	H	B	Si-Si	440	
8	B	0.94	L	B	Si-Si	460	0.1
10	B	0.96	H	B	Si-Si	430	
13	C	0.94	L	B	Si-Si	465	0.2
15	C	0.96	H	C	Si-Si	445	

Information from the manufacturer is used to assign dose values in arbitrary units:
Dose B is ~ 1/10 of the usual LGAD doping,
Dose A is 50% of Dose B
Dose C is 2x times Dose B

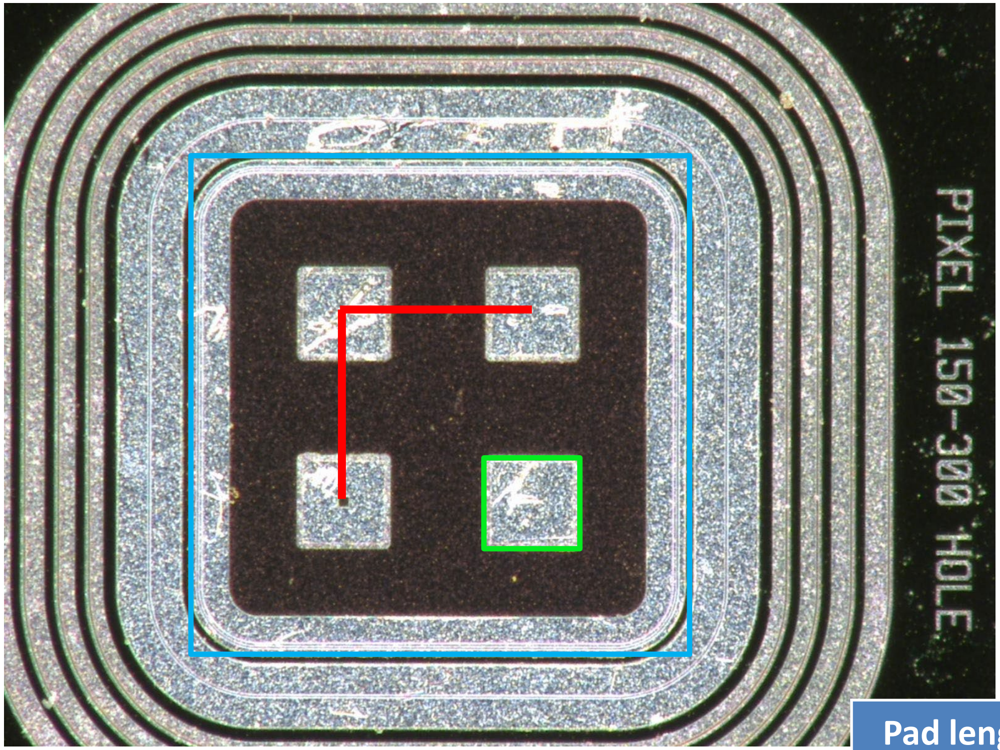
Investigating:

- Dielectric thickness
- n^+ dose

- Measurement frequency
- Pad size
- Neighboring pads

Sample geometry

2x2 arrays, each die with 3 different pad sizes (but same pitch)
→ **varying pad area and distance between pads**



Area of the n^+:
ca. 770 x 770 μm^2

Pitch: 300 µm

Pad length: 150/200/290 µm

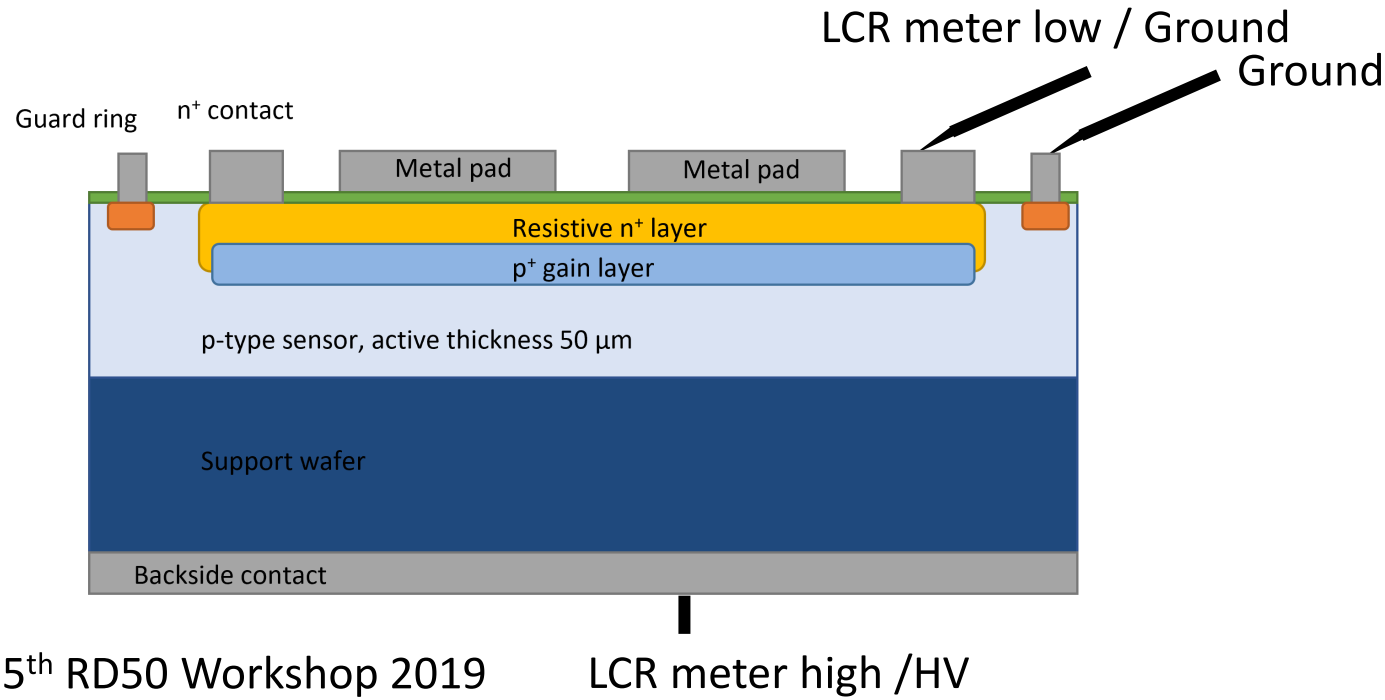
Pad length, width (µm)	Area (µm²)	Interpad distance (µm)
150	22 500	145
200	40 000	100
290	84 100	10

Capacitance measurement configurations

C_p-R_p as LCR meter capacitance model

High voltage always from backplane, biasing ground to n^+

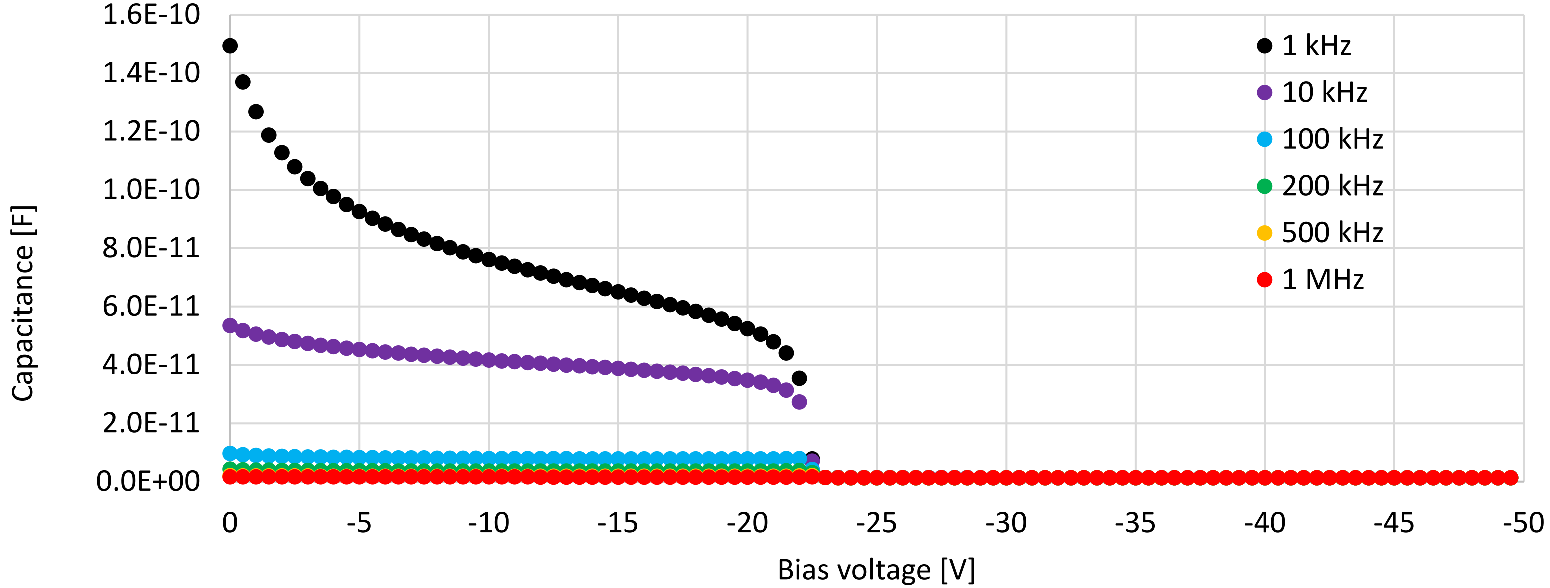
- **DC**: sensor backplane to front side n^+
- **AC**: sensor backplane to metal pad
- **AC-AC / interpad**: between two metal pads
- **n^+ to metal pads**: between n^+ and one metal pad

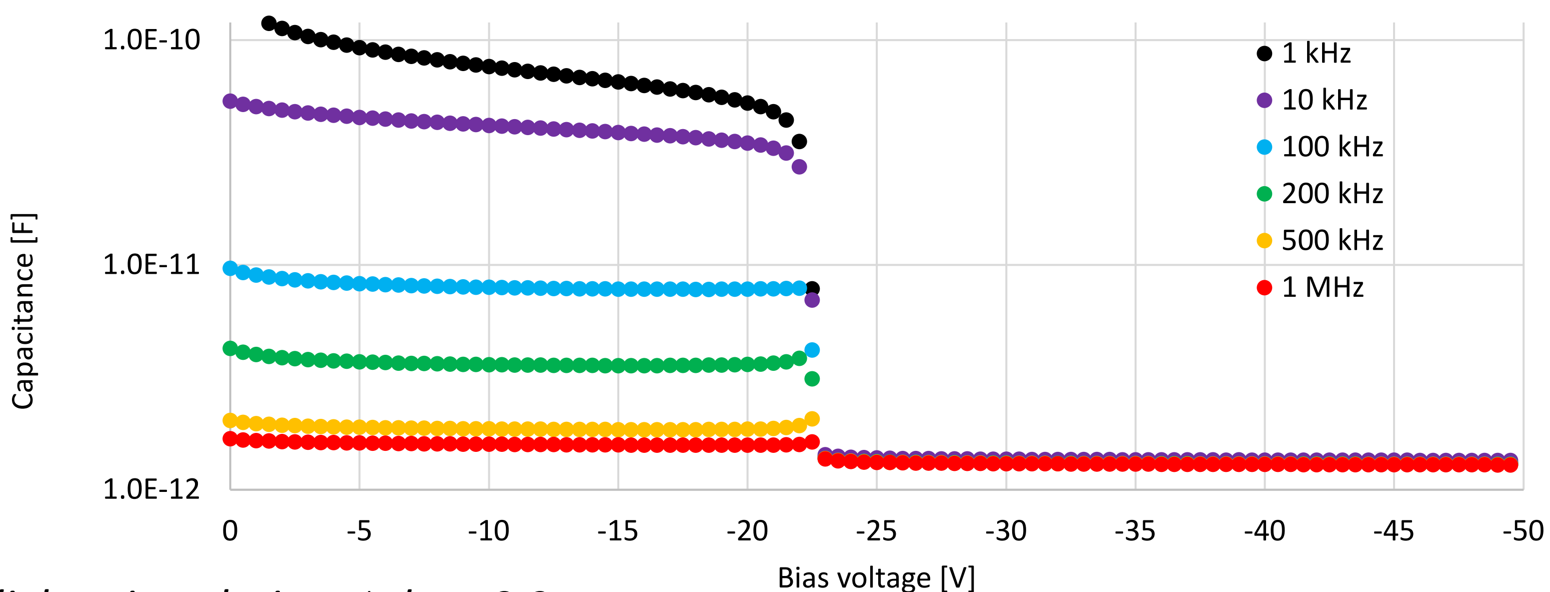


cf. M. Tornago, 35th RD50 Workshop 2019

DC configuration

J. Ott, RD50 workshop Nov 2021

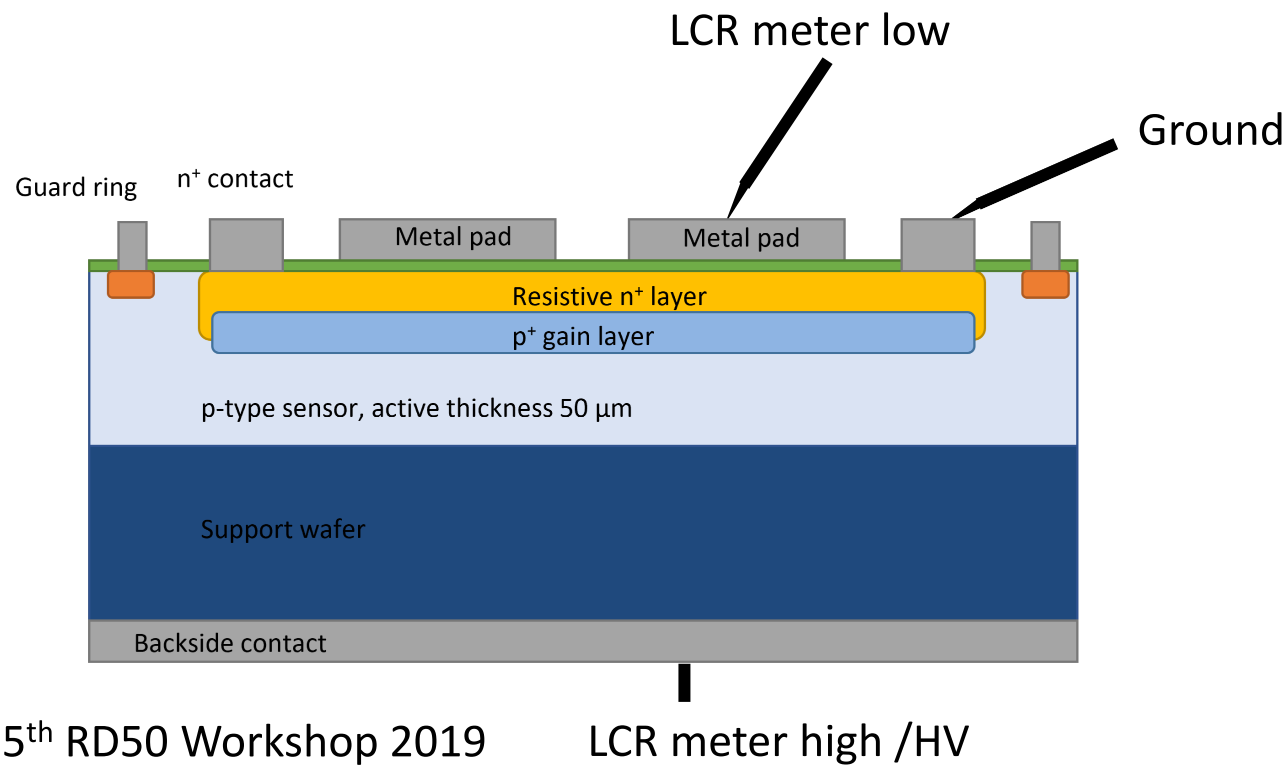




W13, thin dielectric, relative n^+ dose 0.2

Capacitance measurement configurations

- **DC**: sensor backplane to front side n⁺
- **AC**: sensor backplane to metal pad
- **AC-AC / interpad**: between two metal pads
- **n^+ to metal pads**: between n^+ and one metal pad



cf. M. Tornago, 35th RD50 Workshop 2019

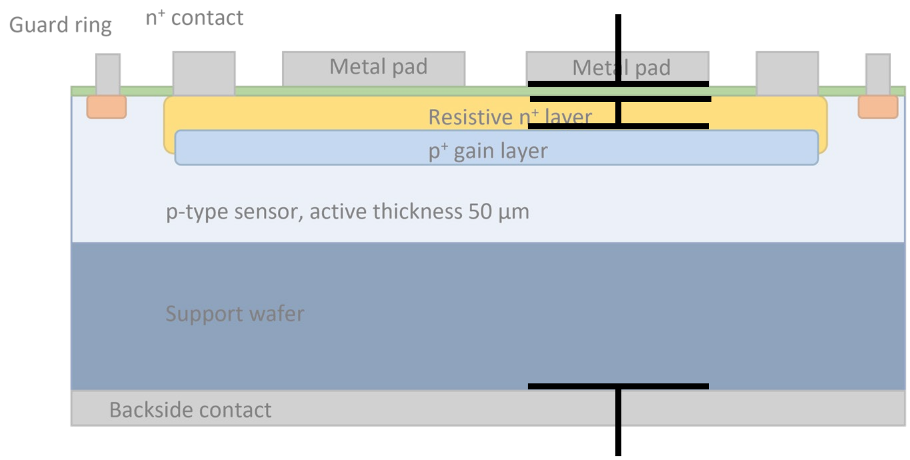
J. Ott, RD50 workshop Nov 2021

Examining the 'AC configuration'

The capacitance of the dielectric layer is orders of magnitude larger than that of Si

$$\frac{1}{C_{tot}} = \frac{1}{C_{Si}} + \frac{1}{C_{dielectric}}$$

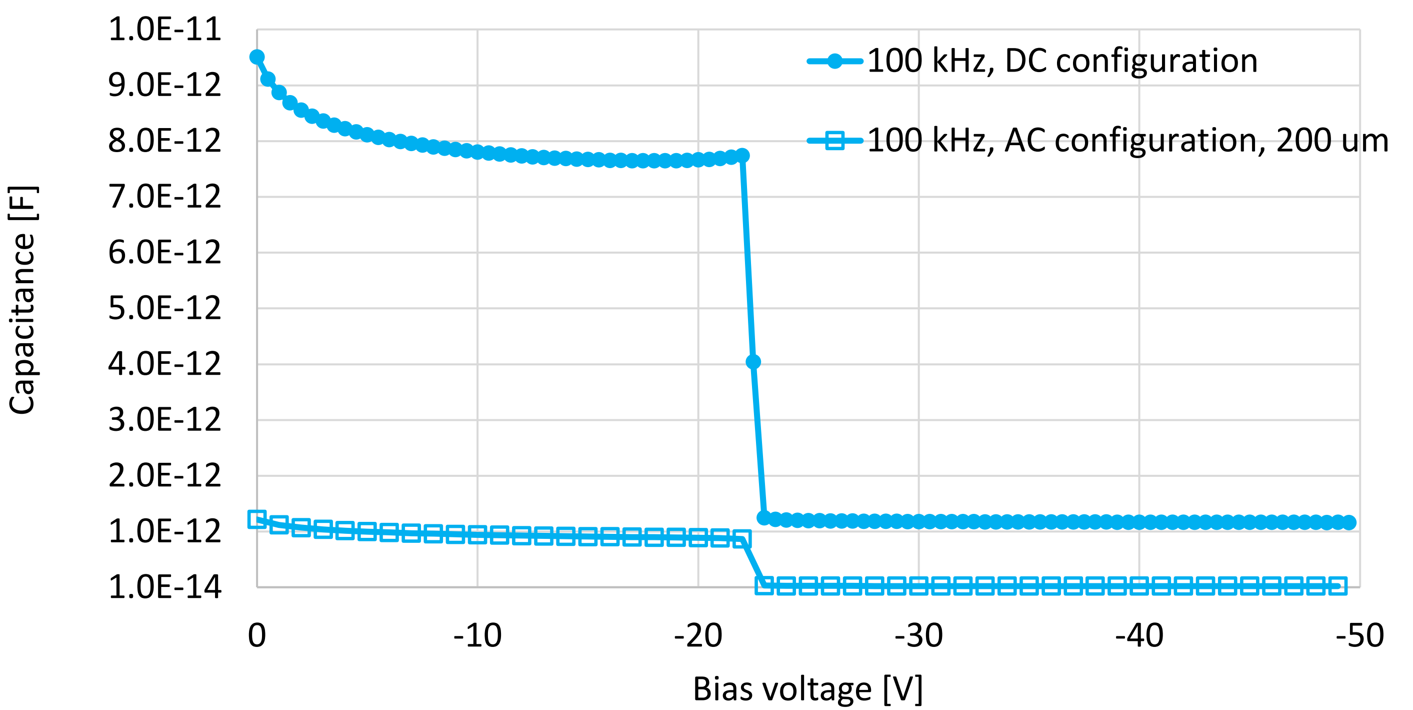
- *If silicon and dielectric capacitance are in series: silicon capacitance dominates!*
- Effective Si capacitance in measurement depends on bias voltage: for the not-depleted sensor, dielectric capacitance is significant - after full depletion, negligible difference



DC and AC configuration

Notable differences in DC and AC configuration:

- Capacitance before depletion in AC configuration is affected by the dielectric capacitance
- Even with the large common n^+ layer, the pad capacitance is determined by the **size of the metal pad**

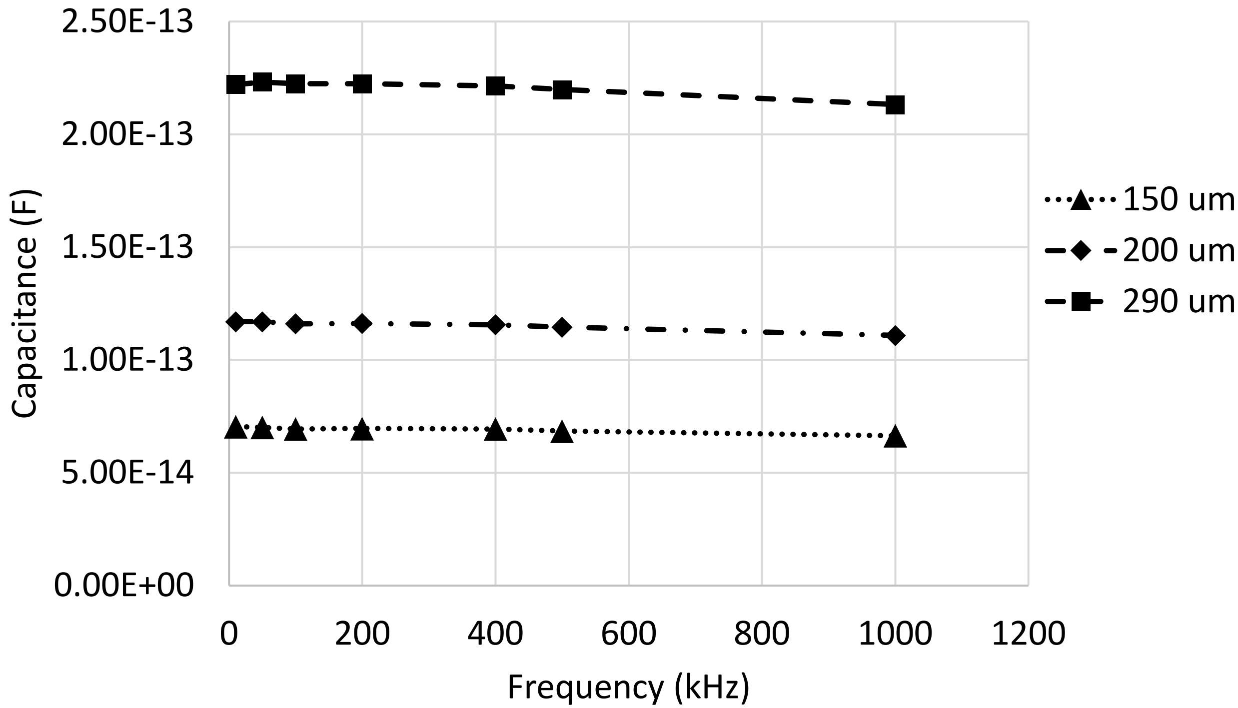


W13, thin dielectric, relative n^+ dose 0.2

AC configuration: pad size

Pad size affects the final capacitance values, since capacitance is directly proportional to the area

- Values after full depletion are relatively small compared to "regular" CV measurements: for 150 µm pads, < 100 fF



W4, thick dielectric, relative n^+ dose 0.05

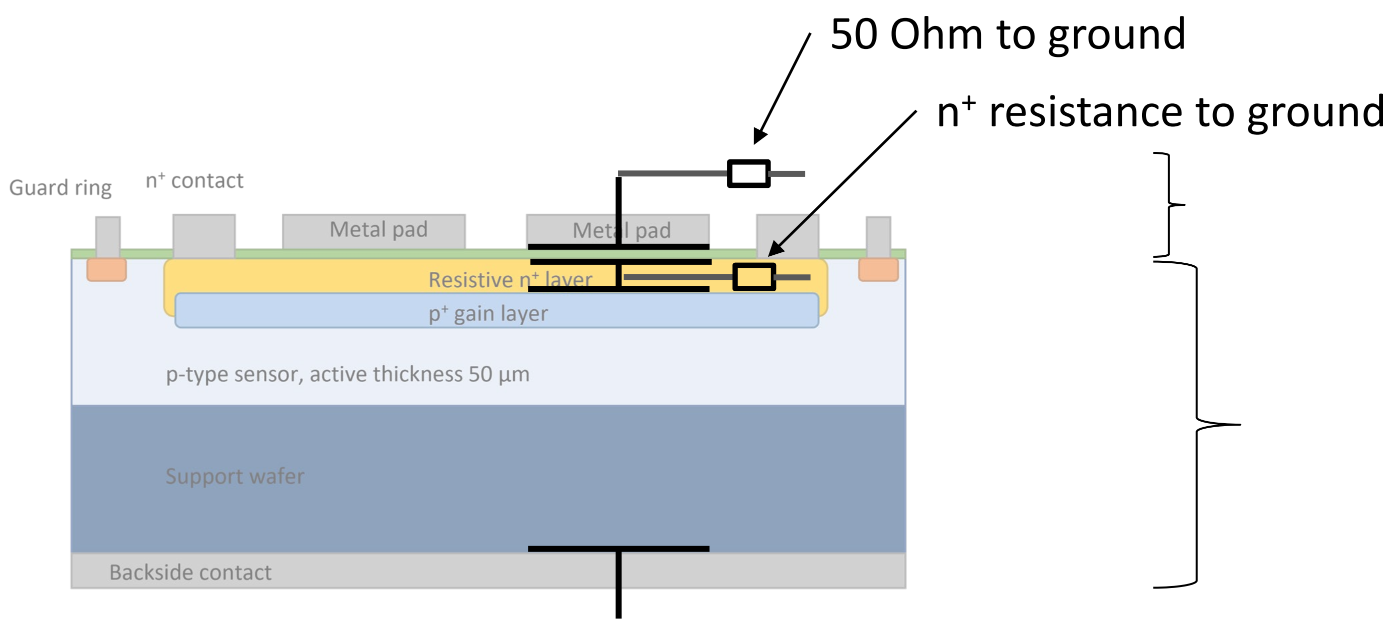
Examining the ‘AC configuration’

The capacitance of the dielectric layer is orders of magnitude larger than that of Si

$$\frac{1}{C_{tot}} = \frac{1}{C_{Si}} + \frac{1}{C_{dielectric}}$$

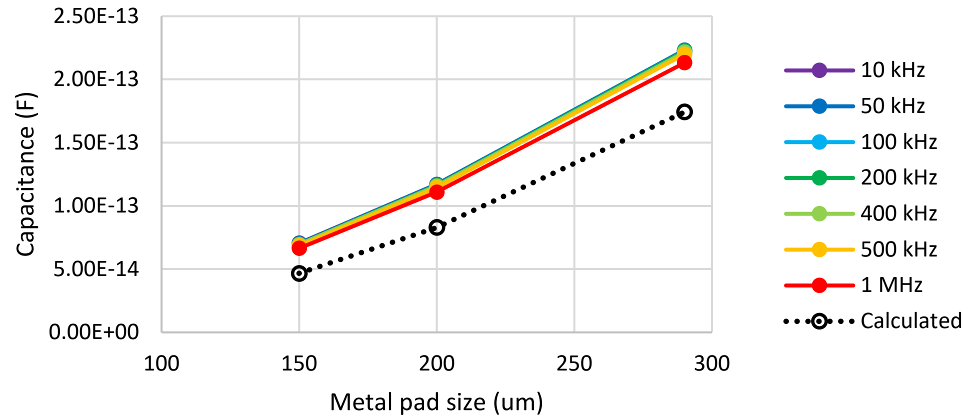
Grounding and n^+ introduce resistances: two CR filters in series

- ➢ Frequency dependence

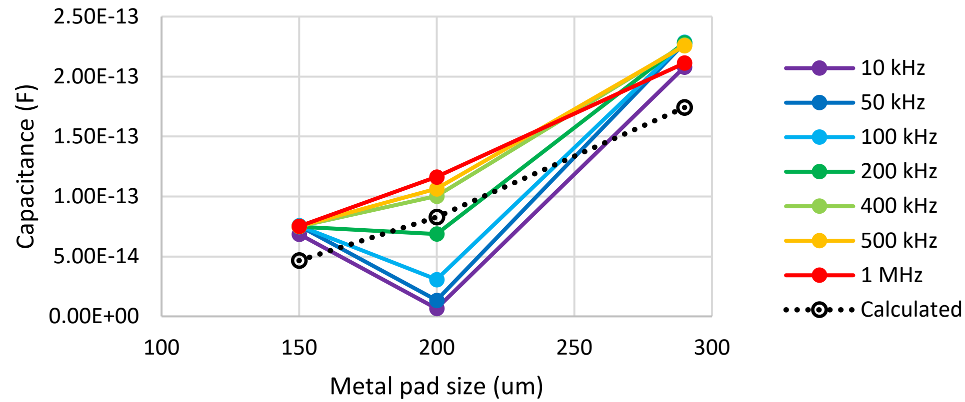


AC configuration: n+ splits (thick dielectric)

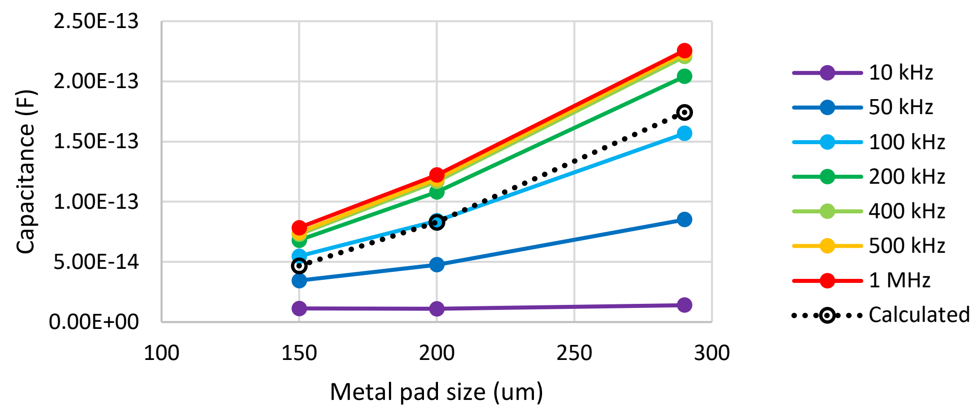
W4, relative n+ dose 0.05



W10, relative n+ dose 0.1



W15, relative n+ dose 0.2

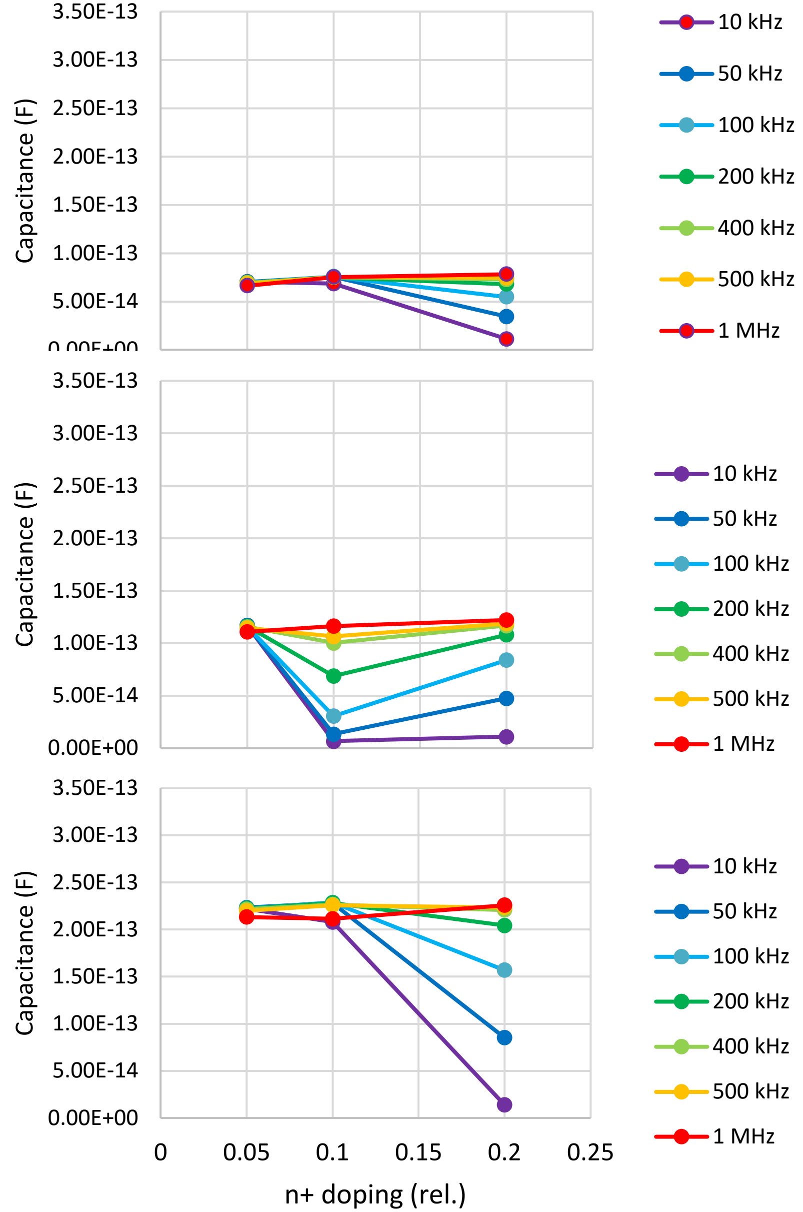


AC configuration: n+ splits (thick dielectric)

150 µm pad

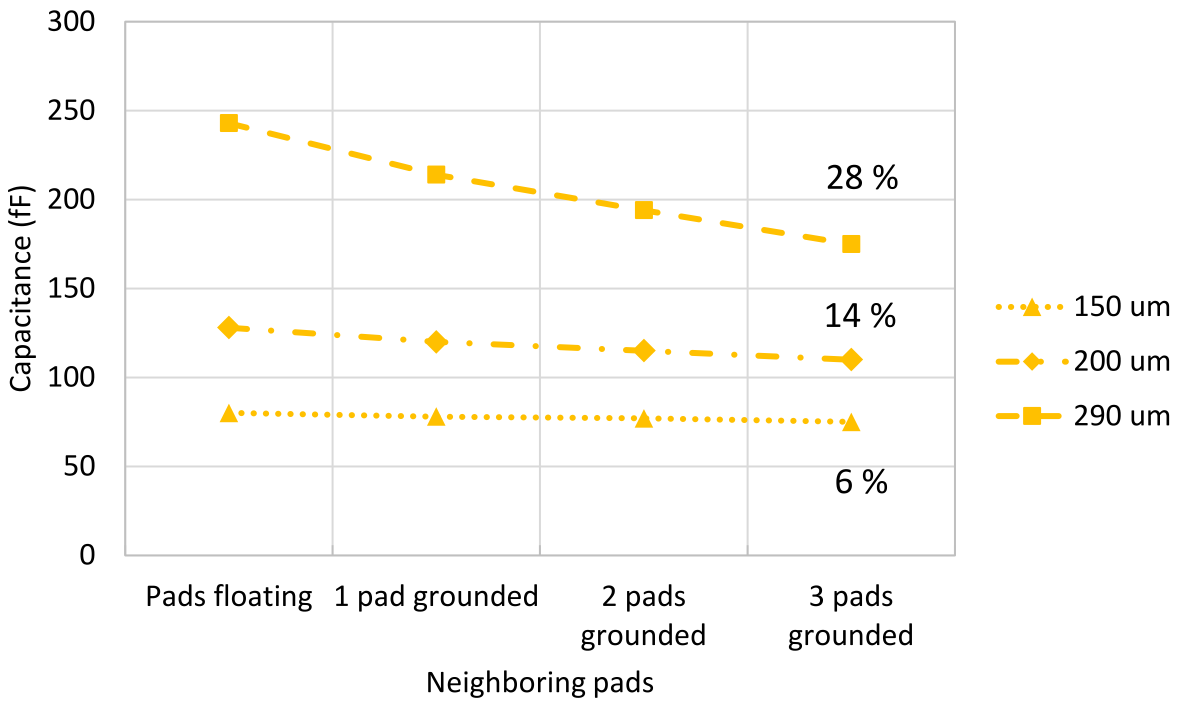
200 µm pad

290 µm pad



AC configuration: grounding of neighboring pads

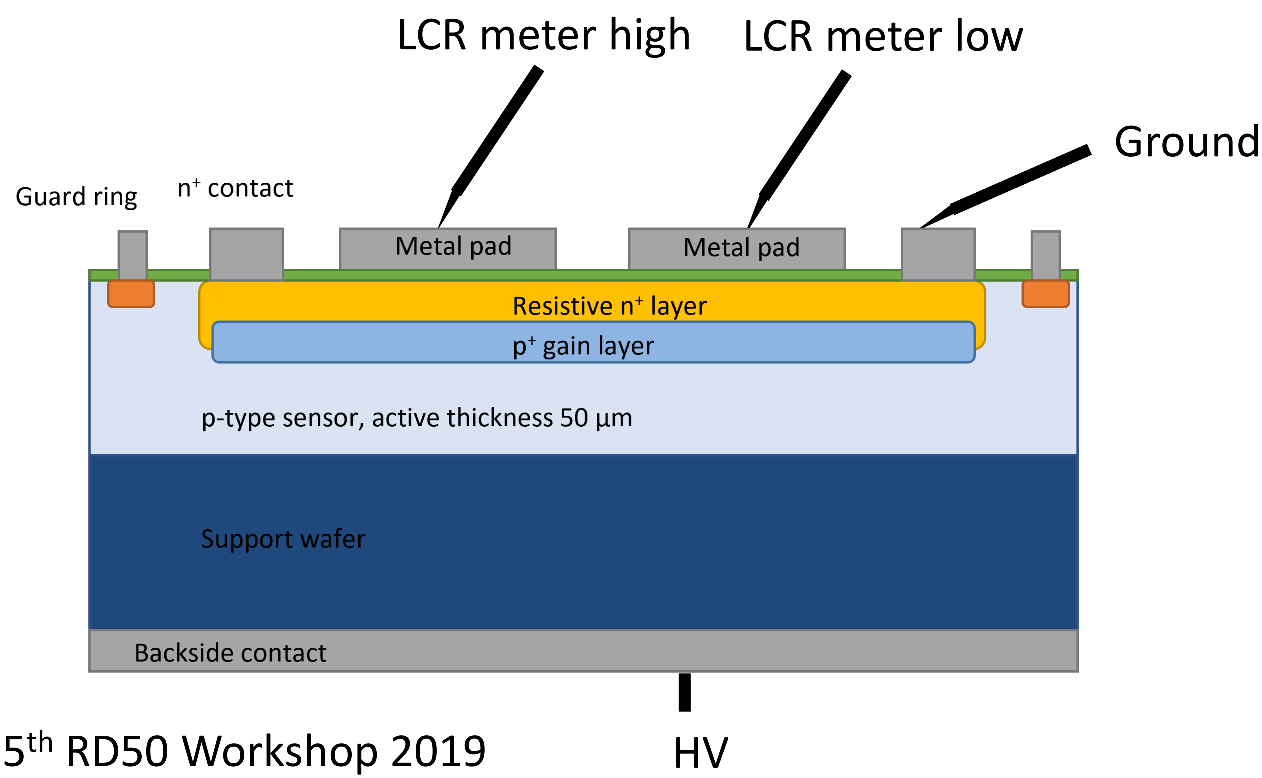
Grounding of the 3 remaining pads impacts the final capacitance value more significantly for larger pads = smaller interpad gap



W4, thick dielectric, relative n^+ dose 0.05. At 500 kHz

Capacitance measurement configurations

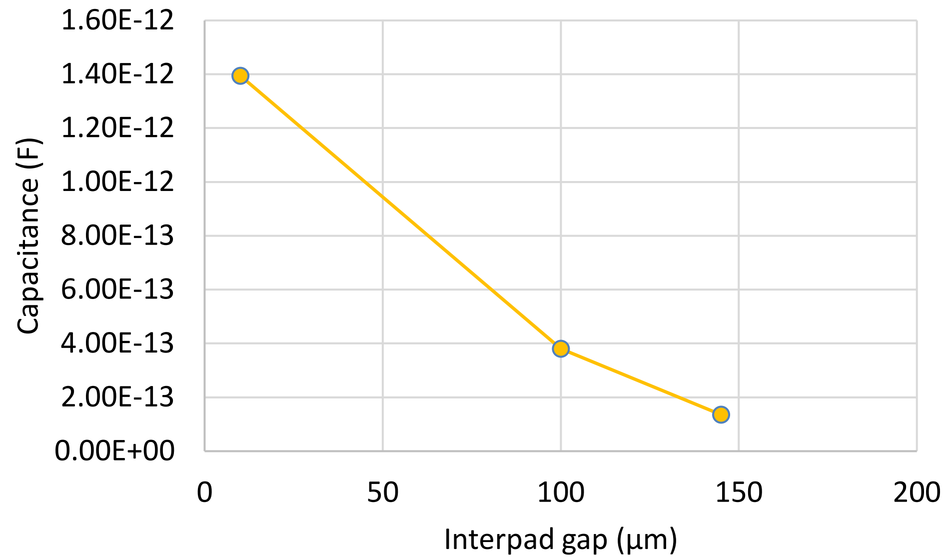
- **DC**: sensor backplane to front side n^+
- **AC**: sensor backplane to metal pad
- **AC-AC / interpad**: between two metal pads
- **n^+ to metal pads**: between n^+ and one metal pad



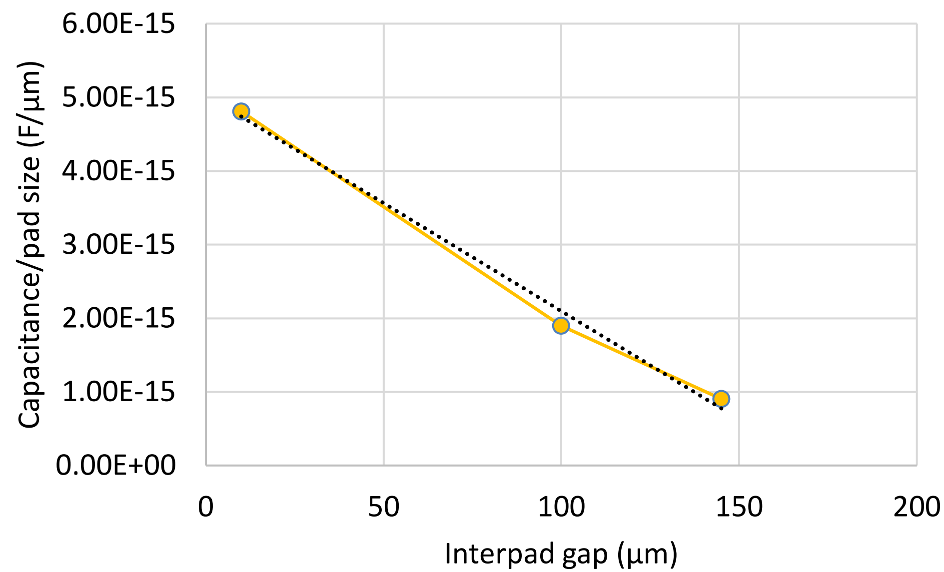
cf. M. Tornago, 35th RD50 Workshop 2019

Interpad capacitance

Interpad capacitance depends on distance between pads



Scaling by the pad size does not quite result in an inverse linear dependence – edge effects?



W4, thick dielectric, relative n^+ dose 0.05. At 500 kHz; other pads grounded

Capacitance measurement configurations

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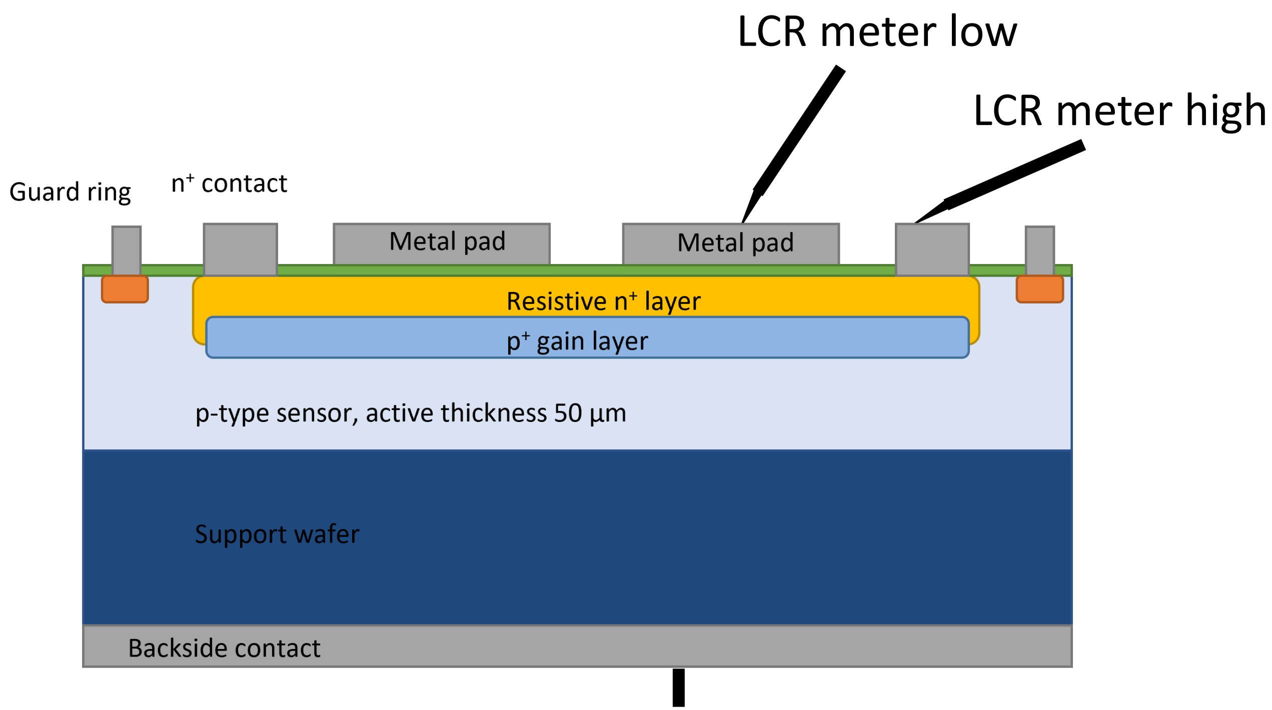

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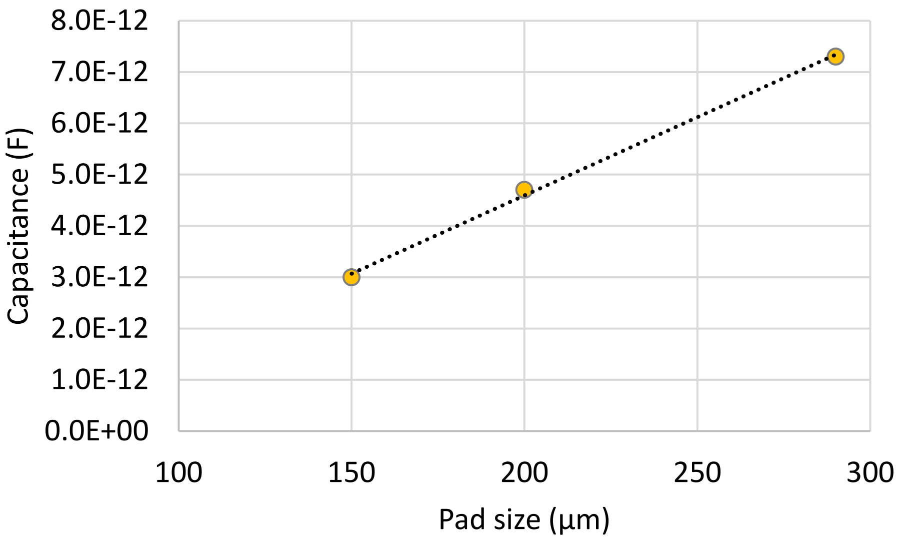
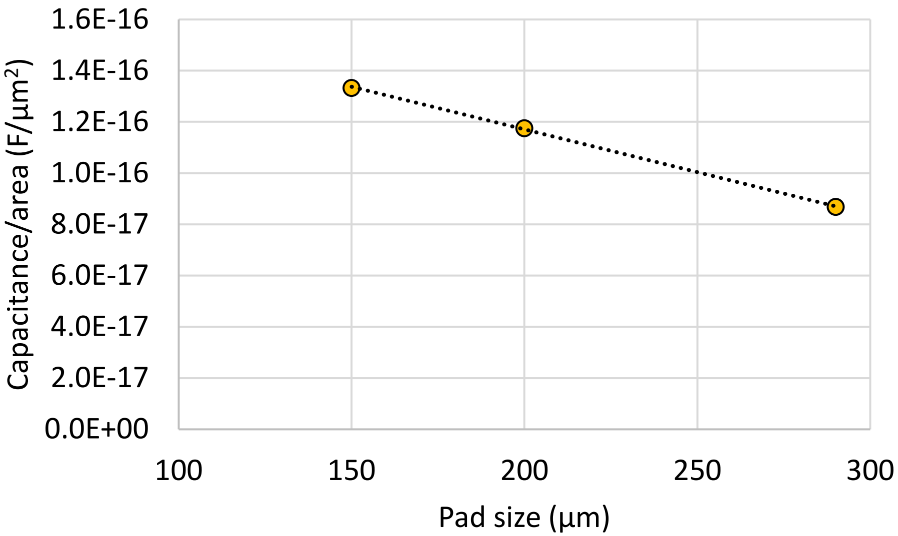
Dielectric capacitance (n^+ to metal pad)

Measured dielectric capacitance depends on pad size and area



Capacitance scaled by area still shows correlation with pad size – edge effects? Effective pad size different from geometric metal pad?



W4, thick dielectric, relative n^+ dose 0.05. At 500 kHz; other pads grounded

Summary

- C-V measurements on AC-LGADs have been conducted in various configurations
- Results are an interplay of pad size, pitch, grounding of other pads, and measurement frequency
- Small pad sizes result in low capacitances
  - More challenging to measure in practice
  - Good news with respect to input capacitance for amplification stage in readout electronics
- Differences in wafer splits (dielectric and n^+ layer) may manifest themselves as dependence on measurement frequency

Next steps

Further measurements on interpad and n^+/metal capacitances

- Aim to disentangle the effects of pad sizes and distances

Circuit simulations of frequency dependence

Conduct similar series of measurements on:

- Other array geometries in FBK RSD1: larger pitches and even smaller pad sizes…
- Recently arrived FBK RSD1 irradiated samples
- FBK RSD2
- AC-LGADs from BNL and HPK

Thank you!

FBK RSD1 production

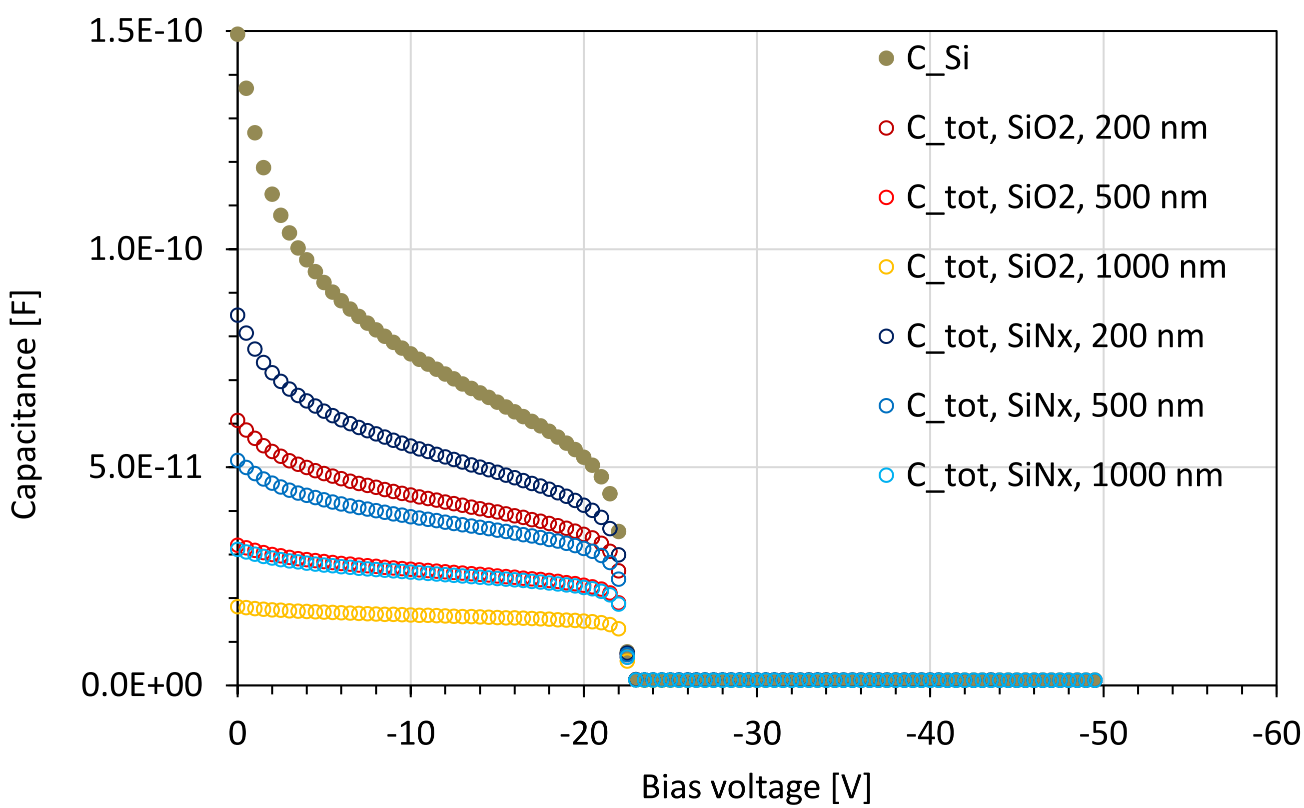
Split table (with breakdown voltage)

wafer	*n* -plus dose	*p* -gain dose	dielectric thickness	*p* -stop dose	substrate	Vbd
1	A	0.92	L	B	Si-Si	480
2	A	0.94	L	A	Si-Si	440
3	A	0.94	L	B	Epi	460
4	A	0.94	H	B	Si-Si	440
6	B	0.92	L	B	Epi	525
7	B	0.94	L	A	Si-Si	460
8	B	0.94	L	B	Si-Si	460
10	B	0.96	H	B	Si-Si	430
11	C	0.92	L	B	Si-Si	515
12	C	0.94	L	B	Epi	490
13	C	0.94	L	B	Si-Si	465
15	C	0.96	H	C	Si-Si	445

Silicon and dielectric capacitance

Calculation of the total capacitance from the silicon capacitance and some potential thicknesses for two different materials:

- Dielectric capacitance is more significant before full depletion



Z - θ

DC configuration

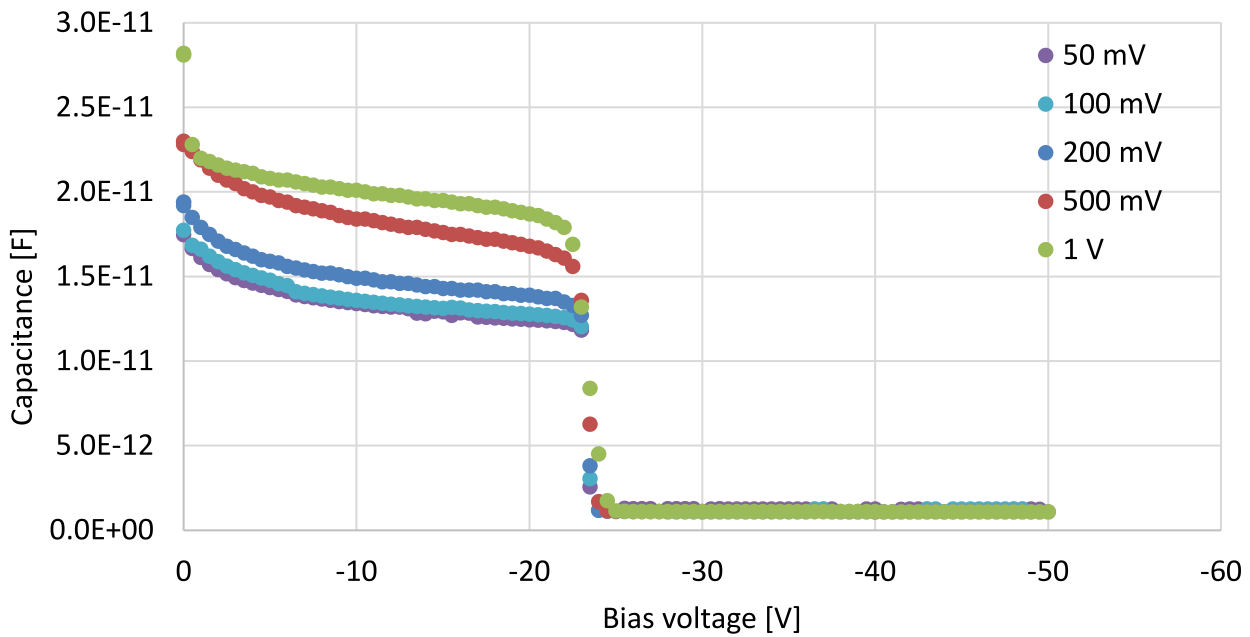
θ ca. -89° when the maximal value for a Cp-Rp model is -90°

AC configuration

θ increases significantly with frequency:
-92° at 1 MHz, -103° for 100 kHz, -160° at 10 kHz

- this is seen as negative Rp
- Frequency dependence is clearly observed, although translation into Cp may not be a valid model

LCR meter AC signal amplitude

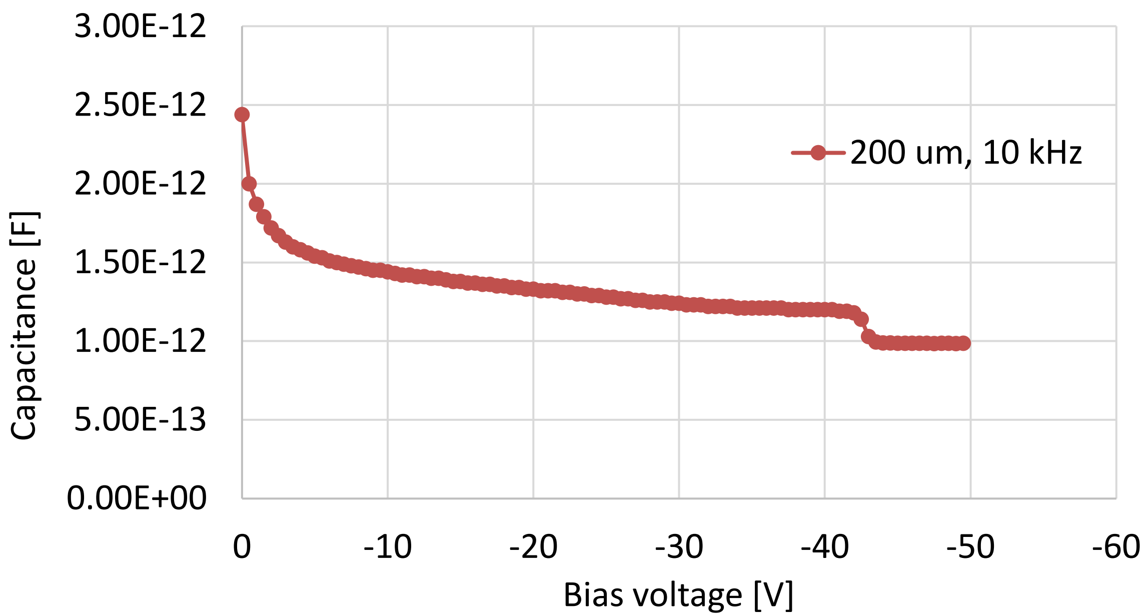


W3, thin dielectric, relative n⁺ dose 0.05. At 100 kHz

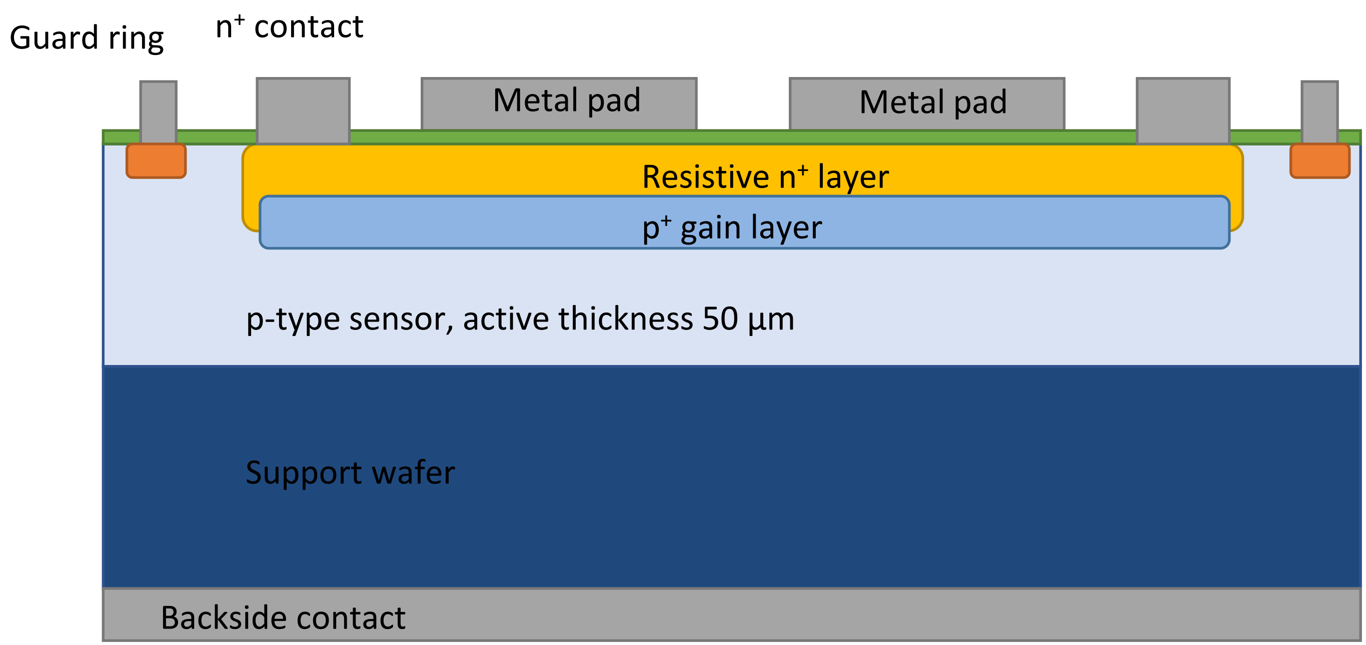
Erroneous measurements

Relatively common observations in the AC measurement configuration, if contact to n^+ is not good:

- Knee appears at > 40V, instead of ca. 23 V
- Final capacitance is closer to the value of the full n+ area than the metal pad



W3, thin dielectric, relative n^+ dose 0.05


Guard ring
n+ contact
Metal pad
Metal pad
Resistive n+ layer
p+ gain layer
p-type sensor, active thickness 50 µm
Support wafer
Backside contact